

Discovery of Hidden Blazars

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A blazar is believed to exist in every radio-loud quasar. This is expected in a unified scheme where the differences in both optical and radio observations of radio-loud quasars are the result of different viewing angles. We have predicted that blazars may be detected using emission line ratio variations caused by variable illumination of gas clouds in the broad emission line region. In a spectroscopic search of 62 quasars at a redshift of about 2, we have discovered large ($>20\%$) variations of the emission line ratios, CIV/CIII] or CIV/Ly α , when compared with historical data taken over 10 years ago. This result is consistent with our prediction, and thus supports the unification scheme for radio-loud quasars.

Quasars are the most luminous of active galactic nuclei (AGN). About 10% of all cataloged quasars are more luminous at radio than at optical wavelengths, and thus are classified as radio-loud quasars. Their strong radio emission arises from two jets shooting away from the center in opposite directions, terminating in extended radio lobes. It is believed that massive black holes and accretion disks are the central engines of all quasars (1,2). However, it is unclear what gives rise to the powerful radio jets. It may be that these jets are produced in the vicinity of only the most massive black holes (3), or perhaps in those with greatest angular momentum (4). Radio-loud quasars are not all alike. However, the diversity in their radio structures and optical spectra can be explained by a unified scheme based on the viewing angle (5,6). If we look directly into the jet, we see strongly beamed synchrotron radiation with the energy distribution peaking in the infrared wavelength. This synchrotron radiation is highly variable and often dominates the light from the quasar's accretion disk and broad emission lines. These objects are classified as blazars. If the line of sight is a few degrees away from the jet direction, we can still see a bright radio core, which dominates the radio power, and this quasar is classified as core-dominant. As the viewing angle is increased beyond a few degrees to the jet direction, the beamed synchrotron emission in radio through optical wavelengths dims. When the jet-lobe structure is viewed at a larger angle, the infrared through optical emission is dominated by thermal accretion continuum and broad emission lines, and the radio core becomes less bright than the radio lobes. These are the lobe-dominant quasars. As the viewing angle is further increased, the quasar continuum and broad line emission are hidden behind an almost edge-on thick dusty nuclear torus or dust in the host galaxy. The only clue to a hidden quasar may be the extended jets and radio lobes. Observationally, this is a radio galaxy.

If the unified scheme (5,6) is correct, every radio-loud quasar should harbor a blazar, and we may be able to observe signatures of the hidden blazars caused by interactions of the beam with their otherwise normal host quasars. Our models have shown that the large flux of beamed infrared radiation from a hidden blazar can heat the broad emission line region (BELR) gas, enhancing collisionally-excited emission lines such as CIV (154.9 nm) and SiIV (139.7 nm) (7). A key signature of this variable heating would be large variations of the line intensity ratios, CIV/Ly α or CIV/CIII], because Ly α , CIII] (190.9 nm) and all Balmer lines are much less affected by the heating. The latter lines are more sensitive to hydrogen-ionizing ultraviolet photons that are scarce in the beamed steep-spectrum synchrotron radiation.

A large blazar outburst may occur once every 10 to 20 years. For example, 3C 279 showed one outstanding outburst in each of two 20-year monitoring periods (8), and each of the outbursts lasted for about one year. During the outbursts this blazar was more than 15 times brighter than usual. Smaller amplitude (a factor of two) variations are also common when it is not in outburst. If every radio-loud quasar harbors a 3C 279 type blazar, we expect to see in every radio-loud quasar variations of emission line equivalent width (EW) ratio (CIV/CIII] or CIV/Ly α) larger than 20% once every ~ 60 years in the observer's frame (for redshift $z \sim 2$ in order for the ultraviolet emission

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lines to redshift into the optical wavelength range, and there is a $1+z$ time dilation factor). Instead of monitoring a few quasars for so many years to look for the predicted line ratio variations, we use an alternative approach, that is, comparing new spectra from a sample of 62 radio-loud quasars with historical spectra taken over 10 years ago. The quasars in our sample have a redshift $1 < z < 3$ and absolute magnitudes $-31 < M_B < -25$. Since 3C 279 spent $\sim 5\%$ of its lifetime in outburst, we would expect to catch three outbursts in our sample during each of the two epochs, or six events with EW CIV/CIII] or EW CIV/Ly α variations larger than 20%. Because of the large range in blazar luminosity and variability, the event rate may be higher or lower than estimated here.

Earlier studies of AGN variability have focused on nearby, low-luminosity, radio-weak objects with known continuum variability, such as NGC 5548, for which it is found (9) that Ly α , CIV and CIII] lines vary with similar amplitudes in response to variations of the normal, non-synchrotron continuum (that may arise in an accretion disk, for example). The amplitude of line variations is usually less than half that of the continuum; this is also true for Balmer lines in a sample of low-redshift ($z \sim 0.1$) quasars (10,11), and a sample of $z = 0.14 - 0.59$ radio-loud quasars, including both core-dominant and lobe-dominant objects (12). Systematic spectroscopic monitoring of luminous high-redshift quasars has not been done before. From photometric studies of large samples of quasars it is found that those of higher luminosity are less variable (13–15). For a quasar in the luminosity range of our sample ($-31 < M_B < -25$), when measured at two epochs, the typical variation is less than 0.2 magnitude (13,14). The expected emission line variations are $< 10\%$ in response to a 0.2 magnitude normal continuum variation. The line ratio variations are even smaller (9,16).

Most of the new spectra were obtained over the years 1998 to 2000, using the Large Cassegrain Spectrograph on the 2.7-m Harlan J. Smith telescope at McDonald Observatory. We typically used a $2''$ slit for long exposures (e.g. 5400 seconds for objects of 18.5 visual magnitude), followed by a short (600 second) exposure with a wide slit ($8''$) to correct the narrow-slit spectra. The seeing was typically $2-3''$ and thus an $8''$ slit exposure is sufficient to correct the shape of narrow-slit spectra for atmospheric refraction losses. During each night usually five standard stars were observed using the $8''$ slit to calibrate quasar continuum shapes. Each of the spectra is wavelength calibrated using argon and neon lamps. Many spectra were taken under non-photometric conditions and thus are not on an absolute flux density scale.

Most historical spectra we used, such as those from (17), were obtained using narrow slits and are not absolutely flux calibrated. Hence, we focus on comparing emission line EW ratio variations. Therefore we used direct division of two spectra to reveal the variability of emission lines relative to the local continuum [e.g. (18)]. A featureless division spectrum indicates that there are probably no variations in the continuum or emission lines, because terrestrial clouds only cause a gray suppression of the spectra, and wavelength-dependent slit losses resulting from atmospheric dispersion cause a low order continuum shape difference. We divide spectrum 1 at one epoch, by the spectrum 2 at another epoch. Avoiding regions of emission lines, we fit a low order curve to this division spectrum, and multiply spectrum 2 by this curve. Thus we normalize the continua, removing the effects of wavelength-dependent continuum variation. Information about changes in the ratios of emission line strengths is preserved unless there is a real variation in the continuum shape. Very little is known on how the continuum shape varies in a quasar spectrum. However, some clues can be inferred from NGC 5548, which appears to be $\sim 17\%$ more variable at 135.0 nm than at 184.0 nm in the rest frame while the average continuum variation amplitude is a factor of two (15). This would cause a 17% apparent emission line EW ratio (Ly α /CIII]) variation in our method of analysis. We note that quasars in our sample are much less variable than NGC 5548, and hence the continuum shape variation is likely to be less than 17%.

For half of the objects in our sample the spectra at the two epochs match well (Table 1, class C). This is consistent with photometric findings that quasars at this redshift and luminosity range are generally not highly variable, so our comparison method appears tenable. Most of the class D objects, which are core-dominant and known to be more variable than lobe-dominant objects (18), could cause the apparent proportional line variations using our method of comparison. Large line variations are seen only in CIV lines (Fig. 1), consistent with our predicted behavior for quasars with hidden blazars.

MRC 0238+100 [$z = 1.83$ (17), $M_B = -27.7$ (19)] has shown an increase of 70% in its CIV line strength between 2 December 1986 and 10 November 1999. A SiIV (139.7 nm) line, not present in the historical spectrum, appeared

in our new spectrum. The SiIV line is more sensitive to infrared heating than the CIV line, and the intensity of the SiIV line may increase by 100% according to our models (7). The appearance of the SiIV line in our new spectrum suggests that the CIV enhancement is due to infrared heating from the additional blazar continuum. The low signal-to-noise ratio near the CIII] line means that we can only constrain the CIII] variation to be $<30\%$. Hence, the variation in emission line EW ratio in this case is $>30\%$ for CIV/CIII] over the time interval of 13 years. From the digitized (red plate) Palomar observatory sky surveys I and II (20) we find for MRC 0238+100 a differential variation of 0.01 ± 0.20 magnitude between epochs 1954 and 1990. Comparing our four new observations on 22 November 1998, 10 November 1999, 2 March 2000, and 1 January 2001, a time interval of 2.1 years (or 0.74 years in this quasar's rest frame), reveals no significant continuum or emission line variations. We suggest that the hidden blazar inside MRC 0238+100 is currently in an outburst, maintaining strong CIV and SiIV line emission with little change in the observed continuum or CIII] emission line. The low activity state of the hidden blazar in 1986 is supported by an earlier observation in 1976 (21), when MRC 0238+100 had line-to-continuum ratios (defined as flux ratios from the line peak to the continuum level. Unfortunately the spectrum was not published) of 2.50 for CIV, and 1.53 for CIII]. These observed line strengths are consistent with the 1986 values while in our new spectrum the line-to-continuum ratios are 3.8 for CIV and 1.6 for CIII], as can be measured from Fig. 1.

UM 556 [$z=2.39$, $M_B=-28.4$ (19)] has a 70% stronger CIV emission line in the spectrum of 5 June 2000 compared with the spectrum of 6 March 1988. The Ly α line is $\sim 10\%$ stronger in 2000 than in 1988. The SiIV line also appears to be stronger in 2000 but with less certainty due to its being a weak line in these spectra. The line EW ratio variation is thus 55% for CIV/Ly α .

If we assume that the blazar outbursts do not last longer than one year in the rest frame as suggested by observations of nearby blazars, we can predict that the CIV line in MRC 0238+100 and UM 556 will drop significantly within the next three years. Even though the hidden blazar's continuum may vary on times scales of less than several months or even days, the observed emission lines are unlikely to vary on these time scales, because the light travel time across the BELR [several light months in high-luminosity quasars (11)] will result in smearing out such variations.

PKS 0038-019 [$z=1.67$ (17), $M_B=-26.9$ (19)] shows a CIV line 43% stronger in 1986 than in 1999, while its CIII] line is 18% stronger in 1986 than in 1999. The line EW ratio (CIV/CIII]) in 1986 is thus 21% larger than in 1999. The emission line intensity variation of CIV is seen in the red wing, suggesting that the part of BELR gas in the beam is moving away from us. This shows the potential of the technique to probe the polar regions of the quasar BELR. However, this case is not as convincing as in MRC 0238+100 because there is uncertainty in matching the continuum at the blue end of the spectra and the historical spectrum did not include the SiIV line. We also derive from the digitized Palomar observatory sky surveys (20) a differential photometric variation of 0.11 ± 0.45 mag. The large error bar may be due to the plate quality and the slight difference in the bandpasses at the two epochs.

For PKS 0424-13 [$z=2.17$, $M_B=-28.6$ (19)], the spectrum obtained on 16 February 1990 shows the CIV line to be 25% stronger than on 20 December 1998, while Ly α is $\sim 10\%$ stronger in 1990 than in 1998. The line EW ratio CIV/Ly α is thus 14% larger in 1990 than in 1998. In addition, the CIII] line shows little variation in this object. The CIV line variation is thus constrained from both ends of the spectrum, ruling out the possibility that the observed line variation is caused by continuum shape variation in this object.

Both MRC 0238+100 and PKS 0038-019 are lobe-dominant with clear double-lobed radio structures (22). The ratios of core to total radio flux density of MRC 0238+100 and PKS 0038-019 at rest frame 5 GHz are 0.098 and 0.067, respectively (23). The lobe-dominant radio structure of PKS 0424-13 is implied by its steep radio spectrum (24). We do not expect to see the variable blazar continuum at such large implied viewing angles away from the beam. While some large apparent emission line variations have been reported in core-dominant quasars with large continuum variations [e.g., (18) reported an EW change of 68% in CIV and 82% in CIII] for 3C446], no large line ratio variations comparable to the cases of MRC 0238+100 and UM 556 have been reported so far, except for the low luminosity AGN NGC 5548 [e.g., (25), where a HeII (468.6 nm) flare was interpreted as an accretion event]. We also note that because 90% of quasars are radio quiet, some of them have inevitably been observed more than once, yet no large line ratio variations have been published (26).

Our observations offer support for the unified scheme for radio-loud quasars. The emission line variations provide the most direct evidence for the existence of a violent blazar in every radio-loud quasar. Similar ideas can be applied to other jet-disk systems such as gamma-ray bursts and proto-stars. In addition, the disk-wind model for the broad line emitting clouds with the winds blowing off the accretion disk by radiation pressure (29) is challenged because it does not include any gas in the polar regions. Another widely adopted model, the stellar atmosphere model for the BELR (30) has been challenged by emission line profile studies (31). Hence, other explanations for the origin of BELR gas may be needed. Finally, the results from this work suggest that radio-loud quasars should be excluded when studying cosmology via the Baldwin effect [the inverse relation between $EW(CIV)$ and continuum luminosity, (32)]. Reducing the scatter in this relationship is critical for using quasars as luminosity indicators (33), while radio-loud quasars introduce extra scatter as a result of their hidden blazar activity.

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Table 1: Classification of emission line EW ratio variability in the sample. The five classes are indicated in column 1. Column 2 gives the number of objects in each class. The number of core-dominant objects is given in the parentheses.

Class	#(c)	Description	Interpretation
A	3(1)	large relative CIV variations ($>20\%$)	outbursting hidden blazars revealed
B	9(3)	smaller relative CIV variations (10–15%)	hidden blazars active
C	33(7)	no $>10\%$ variations in any lines	high- z and high- L quasars not very variable
D	15(10)	all lines vary in proportion	continuum variation at different epochs; emission line response to normal quasar continuum
E	2(1)	10–15% variations in $\text{Ly}\alpha$ but not CIV	continuum more variable in the blue than in the red

Fig. 1.— Comparison of spectra at two epochs. The continua at different epochs have been scaled to the same level. Red solid lines are new spectra taken during 1998–2000. Blue dotted lines are historical spectra taken during 1986–1988. Subtraction spectra (green lines) are plotted in the same panels. The flux level is plotted in μJy [1 jansky (Jy) = $10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$]. In the lower panels the division spectra (before scaling) and the fitting curves are plotted together in arbitrary units. MRC 0238+100, UM 556, PKS 0038–019 and PKS 0424–13 show significant CIV variations with little CIII] or $\text{Ly}\alpha$ variation. PKS 2354+14 and 4C 05.34 are examples of class C objects whose spectra taken at a time interval of over 10 years using different telescopes and instruments are in excellent agreement.

